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A Survey of Codes for Modeling Electromagnetic Launch

William H. Drysdale
John D. Powell
Bruce P. Burns
Alexander E. Zielinski

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William H. Drysdale, John D. Powell, Bruce P. Burns, and Alexander E. Zielinski

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The state-of-the-art in numerical modeling of electromagnetic (EM) railgun launch phenomenology is assessed. It is concluded that among the extensive list of available codes, only two satisfy all of the requirements for electrodynamic calculations. Based on this assessment, recommendations to obtain and validate an EM modeling capability are presented.

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1. INTRODUCTION

Early in 1992, a much needed study was commissioned by the Institute for Advanced Technology (IAT), University of Texas, and the Electrical Armaments Project Office (EAPO), Armament Research, Development, and Engineering Center (ARDEC), to ascertain and document the current state-of-the-art for predictive interior ballistic computational techniques for electromagnetic (EM) railgun systems. The study would also recommend future courses of action for the EM community in general and for the U.S. Army specifically. The agencies that conducted the study were the Los Alamos National Laboratory (LANL), Los Alamos, NM, and the Ballistic Research Laboratory (BRL),* Aberdeen Proving Ground, MD. The findings of LANL are published in another document (Lewis, Rabern, and Meier 1992), while the findings and recommendations of the BRL team are reported here.

The analysis of the interior ballistics of EM railgun systems is especially complicated when compared to conventional gun counterparts. The barrel is not axisymmetric, even for a round bore gun, in either an electrical or a mechanical sense and can only be represented as three-dimensional (3-D). Likewise, the projectile, which may have an axisymmetric geometry, has currents, and hence, distributed propulsive body forces and heat sources (due to ohmic heating) throughout the portions of the projectile which act as an armature that are not axisymmetric. This, in general, requires 3-D analyses to ascertain either the basic propulsive loading or the structural integrity of the projectile system.

The modeling problem is further compounded by the conductive sliding interface between the armature and the rails, assumed by some to be a perfect galvanic contact. This interface is not fully characterized at present (although it clearly depends, at least partially, on temperature and pressure), and offers a continuum of modes of operation from solid through transitioning to full plasma conduction. The details of this contact exert a strong influence on the current path within the projectile, and hence, on the overall performance, affecting such important characteristics as rail erosion. Additionally, it is <u>not</u> reasonable to assume that the rail or gun structure undergoes negligible local deformation during the passage of the shot, so the appearance of gaps at the interface should also be within the modeling capability. The implications of the preceding discussion are that a correct model of EM launch will involve the simultaneous solution of the pertinent electrodynamic, thermal, and structural equations.

* On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

While the simultaneous solution of the combined electrodynamic, thermal, and structural equations would give the "correct" model, it would also require the development and validation of a completely new code of very large scope. A less ambitious course of action is to "weakly couple" existing codes which solve individual subsets of the required equations. Thus, data on the magnitudes of the current and magnetic flux from the electrodynamic code would be used to compute distributed body forces, and this information would be passed to the structural response code. The structural code would use this as input to solve the stress and displacement problem in the projectile/tube/launch system, feeding back data on projectile position and rail motion to the electrodynamic code for future time steps. Likewise, both the electrodynamic code with resistive heating data and the structural code with frictional heating data would feed a thermodynamic code to determine the temperature in the system, with this data passed back to the original codes to model temperature effects on electrical and material properties. If acceptable codes can be determined to solve each uncoupled problem individually, then only an interface manager between the codes is required to pass data at optimum intervals.

Codes sufficient for the computation of structural and thermodynamic variables are believed to be widely available. For example, the DYNA or PRONTO codes developed by the Department of Energy Laboratories will perform the necessary calculations with sufficient generality, and the source codes are usually available for U.S. Government purposes. Other commercially available codes will also perform the necessary computations, but their availability only in compiled form would increase the difficulty of creating flexible interfaces between them and the electrodynamic code. The availability of an adequate electrodynamic code is the major problem addressed in this report.

In conventional gun systems, full 3-D transient simulations have been employed primarily to investigate accuracy-related phenomena, but also to refine structural integrity estimates (Wilkerson and Kaste 1992). Details such as gun tube centerline profile, tube droop, tube response, projectile initial misalignment, and variable clearances for balloting are more or less routinely treated. The interior ballistics of conventional guns is computed from models ranging from sophisticated multidimensional two-phase flow theories to lumped parameter simplifications. The latter has been coupled to a mechanics code to, in effect, model the entire launch phenomenon (Hopkins 1991). Contrasting this level of analysis with that currently being practiced in the development of EM launch systems underlines the necessity of more complete EM simulation techniques before other than Edisonian advances can be made.

2. CRITERIA FOR ELECTRODYNAMIC CODES

A realistic code for solving the electrodynamics problem for both the rails and armature of an EM railgun system must satisfy four basic criteria:

(1) The model must be 3-D. A number of 2-D infinite-rail-height models already exist, but several problems are associated with the calculations. First, the calculations predict a significant overestimate of the in-bore induction fields and forces both in the rails and armature. Some *ad hoc* fixes have been designed over the years to take care of this problem, such as replacing the magnetic permeability by an effective, smaller value (Batteh 1984), but such an approximation is very unsatisfactory in a general scientific sense. Second, the current distribution along the rails is uniform in the third dimension in these models, whereas, in reality, there can be a sizable variation. Third, the models are unable to treat round-bore railguns which are not axisymmetric or planar.

(2) The model must be transient. Current typically diffuses across the armature and into the rails on a time scale of the same order as the total acceleration time, and, consequently, this effect cannot be neglected.

(3) The code must be capable of solving Maxwell's equations in conductors moving at high velocities. Formally, this criterion only involves some additional terms in the equations. However, a phenomenon known as the "velocity skin effect," which tends to concentrate large amounts of current at the corner of the rail-armature interface, can make this inclusion difficult to handle. Furthermore, convective or velocity-dependent terms in diffusion equations can lead to numerical problems.

(4) An energy-transport equation (which is capable of predicting temperature changes arising in the conductors because of both resistive heating and diffusion) must be coupled to Maxwell's equations. The temperature will be coupled to Maxwell's equations through the temperature dependence of the electrical conductivity. The decrease in conductivity with increasing temperature will significantly affect the rate at which the current diffuses through the conductors and the resulting force profiles generated in them.

3. ASSESSMENT OF ELECTRODYNAMIC CODES

The primary emphasis at the present time is in obtaining a realistic solution of the electrodynamics problem. Such a solution is obviously a prerequisite to other types of analysis and is likely to be the pacing problem. There currently exist only two codes which satisfy all the criteria stated in Section 2. These are the codes known as EMAP3D, developed at the Institute of Advanced Technology (IAT) by Hsieh (1992); and the MEGA code, developed at the University of Bath (Rodger et al. 1989; Rodger, Leonard, and Eastham 1991; Rodger and Leonard 1991). Railgun calculations undertaken with EMAP3D are not currently available in the literature. However, personnel at IAT have indicated that one calculation for an armature velocity of a few hundred meters per second has been carried out. The code has not yet been documented although efforts are now underway and it is anticipated to be available by mid-FY93. Calculations undertaken with MEGA have been published in recent EML symposia. The code is available commercially and has been leased in the U.S. by Dennis Keefer, University of Tennessee Space Institute, and purchased by John Barber, International Applied Physics (IAP).

In September, Keefer (1992) indicated that he had encountered some problems with MEGA, particularly at high velocities. The nature of the difficulties was not clear, but presumably current was not always being conserved. Keefer had appealed to David Rodger, University of Bath, from whom he leased the code, for help. Rodger was working on the problems at the time of our inquiry. How severe the difficulties were and the length of time required to remedy them was not known.

Barber (1992) was just beginning to get calculations started with MEGA in late June. More recently the computations are being carried out primarily by Neal Clements (1992), also of IAP. Clements was basically satisfied with the performance of the code, but indicated they had done calculations only at armature velocities of about 10 m/s. He had concluded that calculations at high velocities would require such a dense mesh that they would be impractical for anything but the simplest types of armatures. He did not feel that the code was particularly user-friendly, but did think the University of Bath group was very helpful and cooperative in helping to resolve problems in the analysis.

All calculations which we have seen with MEGA have been for infinitely long rails. As a result of the infinite-rail assumption, important phenomena such as muzzle exit have not been investigated. It is probably not reasonable to try to treat cases in which the breech is not "infinitely" far away from the armature, since the appropriate boundary conditions to use on this end are not apparent; in reality the power supply is connected at this end. However, we can see no reason why the muzzle end could not be arbitrarily close to the armature in a 3-D model. It would then be possible to treat such problems as exit from the muzzle, though these calculations are obviously more difficult than those which have been undertaken thus far.

There are numerous additional codes available for solving Maxwell's equations for various types of problems. However, none presently have all four of the basic criteria listed and described in Section 2. The following is a description of some of those codes.

• MacNeal-Schwendler (MSC EMAS) - This is a versatile 3-D transient code which has even been used to solve some highly simplified railgun problems. According to Mark Janech (1992), MacNeal-Schwendler technical representative, the code cannot presently handle moving conductors nor does it have an energy-transport equation coupled to Maxwell's equations. Janech did say that MacNeal-Schwendler was generally interested in undertaking contractual work to make developmental improvements in their computational capability. The code runs on workstations, and MSC NASTRAN (at ARL) can easily make use of the forces generated in EMAS for structural analysis.

• Rockwell (Hall 1992) - Rockwell investigators have had vast experience in the development of wave-propagation codes in which Maxwell's equations are solved in the 3-D high-frequency limit. They have extremely good post-processing capabilities and can produce good graphical presentations. The codes are used to calculate, for example, EM-wave scattering and radar cross sections. Presumably, Rockwell is interested in extending their computational capabilities to the types of problems in which we are interested. Rockwell estimates that the time required to make the necessary modifications to their codes to be about 1 man-year. We are not sure about the computer requirements for these codes, but Rockwell seems to prefer parallel processing.

• WTD/ARL - The EMP Effects Branch, previously of Harry Diamond Laboratory at Woodbridge, has demonstrated significant computational capabilities in regard to EM problems through the use of various 3-D transient codes. Again, problems addressed have been relative to scattering or radiation. Their codes do not presently have criteria (3) and (4) (Section 2). Personnel there have expressed some interest in the problem, but gave no real indication of the length of time required to make the necessary modifications (Miletta 1992).

• LANL (MAX3D) (Cook 1987) - This code was presumably developed to analyze EM gun problems, and relevant approximations, such as neglecting the displacement current, are made. No velocity-dependent terms appear to be included in the governing equations, and it is not clear whether the code would be capable of handling such effects. We have seen no calculations undertaken with this code.

• UT-CEM (Long 1987) - This code is 2-D finite element, but satisfies the other criteria mentioned. It was the first 2-D numerical investigation of this problem. Maximum velocities reported in any calculations were of the order of 1 km/s, but it is possible that higher velocities could be computed with some effort. The code is very amenable to changes in geometry. The really severe limitation, of course, is that it is only 2-D. A very similar code was described at a recent EML symposium by some investigators from TNO PML Pulsed Physics in the Netherlands (Schooldemian, Zeeuw, and Koops 1993). Most of their work seemed to be concerned with the engineering design of armatures.

• WTD/ARL (Powell, Walbert, and Zielinski 1993) - The Survivability Concepts Branch of ARL has developed an in-house code which is 2-D, very similar to Long's code, and also satisfies the other criteria. Highest velocities computed are on the order of 1 km/s, but no attempts have been made to test the velocity limit of this code. The code is implicit finite difference.

• Swanson Analysis (ANSYS 1989) - The structural module of this code is currently available at ARL. The EM module was presumably developed to provide some electrodynamic capabilities in existing structural codes. The transient version appears to be only 2-D and does not treat the moving-conductor problem. Most of the emphasis and sophisticated calculations seem to be of static problems. The code is PC compatible.

• Others - Other similar examples of PC-based 3-D transient EM codes which can be coupled to structural analysis codes include COSMOS/M and NISA II. They are currently unable to treat moving conductors or energy transport. The cost for this type of software is reasonable (~$10K).

From the results of this investigation, it is concluded that there are three options for obtaining this type of computational capability:

(1) Buy or lease MEGA. Obviously, such an action must be based on the assumption that the problems with the code are minimal and can be worked out quickly. Some support from the University

of Bath group is included with both leasing or buying outright. Both Keefer and Clements have been very impressed with the capabilities of the University of Bath group, as well as their willingness to help.

(2) Obtain EMAP3D when it becomes available to the community. The prognostication is that this code will be available in the near future—mid-FY93. We have no data from which to judge the ease with which this code can be used, but apparently IAT intends to provide some support for users. It would probably be well to support Hsieh of IAT to help make the code suitable for problems of interest to us and to instruct personnel in its use.

(3) Support someone who has a 3-D code for solving Maxwell's equations and have them make the modifications necessary to include all four criteria indicated. Possible choices of appropriate personnel are the people with Rockwell or MacNeal-Schwendler, since both groups have extensive experience in numerical modeling of EM problems and have demonstrated past successes. With any of the options, it would be advisable to have resources dedicated full time for obtaining the code, setting up graphics, and actually carrying out calculations.

Selecting Rockwell for support to further develop their code seems to provide a backup capability. First, Rockwell has an impressive and documented capability in solving a difficult wave-propagation problem, and a previous good working relationship with the ARL. Second, they could be of considerable assistance in helping us couple the electrodynamic code to a structural code, as well as in making other modifications for future types of problems of interest. Third, there are reportedly problems with MEGA; the origin and duration of these difficulties are not known. Fourth, EMAP3D is not currently available, and we have no data from which to judge its capabilities relative to railgun problems. Finally, it would seem pragmatic to obtain some results independent of the MEGA code, since this code is the only one that has been used in the past to undertake these types of calculations.

There are disadvantages to embarking on a reasonably long-term research project with Rockwell, the most obvious being that users will be about 1 year behind those people who currently have MEGA up and running and 6 months behind EMAP3D. On the other hand, Rockwell will be able to provide assistance in coupling the electrodynamic codes they develop to structural codes as the development occurs, as well as in making modifications to handle other problems of interest. Clearly, they will need some continuous guidance in what specific railgun calculations to undertake. We would suggest that initial work be devoted to a 2-D test problem with a rectangular armature so that the results could be compared to existing

2-D calculations. We, in fact, suggested that problem as an initial effort to Rockwell a few years ago when they first expressed some interest to us in these types of calculations.

We also should point out that these codes, in and of themselves, are not a panacea for solving all the problems associated with railguns. All the codes, for example, currently treat the interface between armature and rails as being surfaces in perfect ohmic contact. There is a vast amount of evidence that this assumption is not correct, and there is much physics yet to be understood about these contact surfaces. We hope that there will be some emphasis on looking at these basic, rather than strictly numerical, problems. We also hope that numerical techniques developed will be sufficiently robust to handle the physics of the interface once this information becomes available.

4. ADDITIONAL MODELING CONCERNS

There are several modeling concerns which we feel cannot be reiterated too often. First, and foremost, the interface physics between the rails and the armature must be studied in depth if deterministic simulations of the interior ballistics of railguns are to be made. Such studies will necessarily involve the quantification of current flow as defined in the presence of variable mechanical stress and deformation states, friction, localized material phase changes, and temperature gradients; and will undoubtedly require laboratory-level experimentation to validate physical models. Successful studies of these phenomena are critical to understanding railguns, indispensable in conducting the necessary coupled calculations to optimize gun and projectile configurations required to investigate rail erosion, and should be initiated as quickly as possible.

Secondly, a 3-D EM code is required to properly couple to mechanical codes to capture structural and heating effects not only in the projectiles, but also in the rails and gun structure. In general, the developed methodologies should encompass anisotropic effects as introduced by continuous fiber composite materials, for such materials are emerging as probable candidates for effective projectile and gun structure components. It should also be stressed that the actual effort necessary to couple the various aspects may, in fact, be quite large and computationally difficult, although not intractable.

Thirdly, appropriate means should be employed to ensure that the EM state-of-the-art is appropriately understood. Issues such as the quantification of nonlinear constitutive effects, numerics as related to both accuracy and stability, and material property databases need to be explored to avoid long-term chronic issues that might preclude the exploitation of developing computational methodologies.

It is clear that engineering approaches can be used with existing or slightly improved simulation techniques to derive conservative designs for testing. Such techniques should probably be devised (a design protocol) and applied in the design of contemporary test hardware with the full understanding that such approaches, while providing designs that should work (or at least define probable modes of failure or areas of risk), will probably not yield designs that are very near to optimum insofar as ballistic performance is concerned.

5. RECOMMENDATIONS FOR FUTURE ACTION

In the short term, the only EM codes believed to be able to meet all of the requirements are MEGA and EMAP3D. These two codes should be obtained and compared side by side by several investigators to judge their respective abilities. While the existing features of the EMAP3D are currently in flux, a final version of the code with complete documentation has been projected for mid-FY93. If this date is met, the code should be considered in any attempted downselect.

The situation with MEGA is complicated, due to the proprietary nature of the code and the fact that the code is marketed in the U.S. in executable, but not source, form. In this form, the code could not be modified by users, and any changes (e.g., to allow the listing of body forces or ohmic heat generation at specified solution steps) would have to be made by the University of Bath developer. This situation would probably be an untenable position, although the developer claims to be anxious to please. A better situation would be for source code to be available, perhaps only to the U.S. Government, so that the required changes to MEGA could be made and passed on to contractors and the EM community who have current lease or buy arrangements with the developer. These proprietary details could take as long to resolve as any technical questions, and so should be addressed immediately so that some feel for an outcome would be available in time for a downselect. The possible involvement of RARDE with an attempted coupling of MEGA/DYNA should certainly be investigated, both as leveraged technical effort and as an entry to a request for source code.

The codes MEGA and EMAP3D should be thoroughly benchmarked against each other with regard to the same problem for:

- accuracy of solution, compared to accepted 2-D codes and known 3-D solutions (not necessarily experimental)
- run time and memory requirements
- ability and ease of modeling accelerating projectiles
- ability to continue accurate solution to high velocity
- ensuring body force and heat parameters are available as output for finite element structural analysis at any specified time step

The heat equation may be solved in either the EM or the structural code. Note that either code will have separate heat generation terms which must be passed to the solver. The EM code has ohmic heating, the mechanical code has frictional heating and energy dissipation from plastic deformation, and material melting or vaporization may be occurring. If the solution is to occur in the EM module, it must accept input at each time step corresponding to heat generated by mechanical sources.

As discussed previously, both codes use moving rails flowing past a stationary projectile.* While coordinate transformations connect this model to the real situation, the computation is normally done with infinite rail lengths. This simplification may be necessary at the breech end, where the boundary conditions corresponding to the power supply are unknown. However, muzzle approach and shot exit are phenomena which must be studied. Therefore, the ability of the two codes to handle the approach to the muzzle, and even exit, should be compared carefully.

A related but more complicated issue involves the ability of these codes to handle uneven or gouged rails, balloting or tipped projectiles, tube deflection, etc. As long as perfect electrical contact is assumed at the interfaces, this, of course, is a non-issue. However, if the contact behavior eventually depends on interface pressure, open gaps, or other real effects, the ability to capture these features should be assessed. both for the moving rail model in general and for each of the studied codes in particular.

Approximately 6 months after the two codes are obtained and debugged, it should be possible to downselect to a single code best suited for coupling with a selected mechanical finite element code. The

* The version of EMAP3D discussed in this report has recently been modified. Calculations are now done in the laboratory frame of reference where the rails are fixed and the armature moves.

work of coupling these codes could then proceed. All of these considerations presume that sufficient assets are bought to bear to adequately address the problem in a timely fashion.

We also suggest the parallel funding of Rockwell to develop a 3-D EM code into one able to solve railgun problems and meet all the stated requirements. This code could have the more standard (in conventional ballistics) coordinate system of a fixed breech, flexible tube, and accelerating projectile, and so the ability to model the above conditions would be relatively straightforward. Rockwell has estimated a 1-year task to develop the EM code, so the new code should be available 6 months after EMAP3D. Again, this alternative should be considered as a backup in case neither existing code can meet some specification such as muzzle exit conditions. The different formulation would be unlikely to suffer the same disadvantages and would give an independent solution. The parallel development would eliminate 1 year of time should the code prove necessary. The cost is, of course, the expenditure of additional fiscal resources.

Finally, it is recommended that small, focused workshops be held periodically. Issues to be covered should include numerics and computational requirements; comparison of results from evolving codes with existing experimental data and earlier calculations; material properties; and new developments in relevant physics.

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